

Review of Sensor & Sensor less Control Topologies for a Four-Switch Inverter Fed Permanent Magnet Brushless Dc Motor

Y. V. Aruna*, A. Mallikarjuna Prasad**, E. Ramakrishna***

*(Department of Electrical and Electronics, St.John's College of Engineering & Technology, Yemmiganur)

** (Department of Electrical and Electronics, St.John's College of Engineering & Technology, Yemmiganur)

*** (Department of Electrical and Electronics, St.John's College of Engineering & Technology, Yemmiganur)

ABSTRACT

Permanent Magnet (PM) Brushless DC machine has distinct advantages of high efficiency, high power density, high power factor, high torque, simple control, and minimal maintenance. Modelling, simulation and experimentation of drives with new converter configuration and control schemes are essential for making this drive competitive. This paper describes modelling of four switch inverter fed BLDC motor, is explained with transfer function model. The simulation of sensor and sensor less control of drive is done in Matlab/Simulink. Control with sensor, the controller is used Fuzzy logic Controller and in sensor less control the method is used is terminal voltage sensing

Keywords- Fuzzy logic controller, PMBLDC Motor, sensor less control, Simulation models.

I. INTRODUCTION

Permanent Magnet Brushless DC (PMBLDC) machines are more popular due to its simple structure and low cost. Improvements in permanent magnetic materials and power electronic devices have resulted in reliable, cost effective PMBLDC drives, for many applications. Since the late 1980's new design concept of permanent magnet brushless motors has been developed. The permanent magnet brushless motor can be classified upon to the back-emf waveform, where it can be operated in either brushless AC (BLAC) or brushless DC (BLDC) modes. In modern electrical machines industry productions the brushless direct current (BLDC) motors are rapidly gaining popularity. BLDC motors are used in industries such as Appliances, HVAC industry, medical, electric traction, road vehicles, aircrafts, military equipment, hard disk drive, etc. For extensive system testing and evaluation program, detailed computer modelling and simulation is being developed. Modelling of the PMBLDC machine and the controller are essential for evaluating their performance. The low cost BLDC driver is achieved by the reduction of switch device count, cost down of control, and saving of hall sensors for commercial applications.

BLDC motors are electronically commutated based on the rotor position. Each commutation sequence has two of three phases connected across the power supply and the third phase is left open. The market is too competitive so cost reduction and higher performance will be the prime importance. Cost reduction in BLDC motor drives can be achieved by two methods one topological approach and second control approach. In the topological approach, the number of switches, sensors and associated circuitry used to compose the power converter is minimized. In

this paper Simulation model using transfer function of BLDC motor is presented.

II. Mathematical modelling of BLDC motor

The dynamics of the machine are described by a set of differential equations the three phase star connected BLDC motor can be described by the following basic equations. To attain the electrical equations for a BLDC machine, basic circuit analysis was used to find the per-phase voltage as shown below. These are per phase modelled equation. A per phase model is also shows in figure 1.

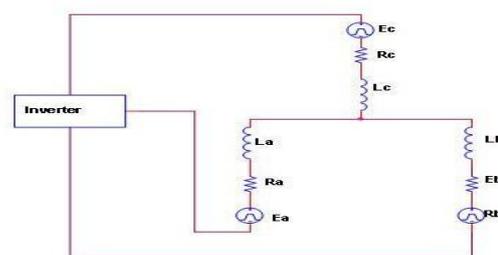


Figure 1. Equivalent circuit of BLDCM

$$V_a = i_a(t)R_a + L_a \frac{di_a}{dt} + e_a(t) \quad (1)$$

$$V_b = i_b(t)R_b + L_b \frac{di_b}{dt} + e_b(t) \quad (2)$$

$$V_c = i_c(t)R_c + L_c \frac{di_c}{dt} + e_c(t) \quad (3)$$

$$T_{em} = B\omega(t) + J\frac{d\omega(t)}{dt} + T_L \quad (4)$$

Where V, I and e are the voltage, current and back-emfs of phase A, B and C. R and L are the resistance and inductance of each phase respectively. T_e and T_L are electrical torque and load torque, j is the rotor inertia, K_f is the friction constant and ω is the rotor speed.

But we know that Electromagnetic torque and back emf are given by equations (5) and (6).

$$T_{em} = K_t i_a(t) \quad (5)$$

$$e_a(t) = K_e \omega(t) \quad (6)$$

Where k_t is torque constant and k_e motor constant. Where k_t is torque constant and k_e motor constant. Taking Laplace transformation of the respective equations and rearranging the terms equations (7) and (8) are obtained.

$$\omega(s) = \frac{I_{sm}(s) - T_L}{B + sJ} \quad (7)$$

$$i_a(s) = \frac{V_{an}(s) - K_e \omega(s)}{R_a + sL_a} \quad (8)$$

From the above equations it is possible to draw the model of the BLDC motor as shown in Figure 2. from the Figure 2 transfer function of the system is presented in equation (9).

$$\frac{\omega(s)}{V(s)} = \frac{K_t / JLa}{s^2 + \frac{JRa + BL_a}{JLa}s + \frac{BR_a + K_t K_e}{JLa}} \quad (9)$$

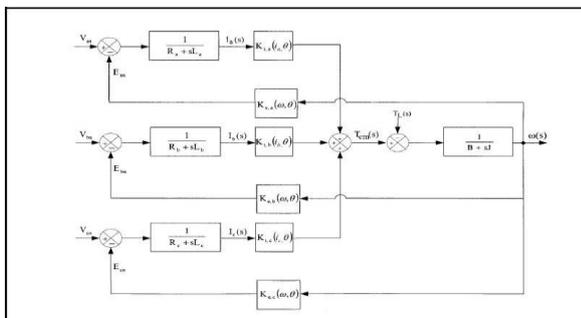


Figure 2. Transfer function model of PMBLDC

III. Four Switch Converter Topology

In conventional six switch inverter topology a 30° phase delay is to be carried out between the zero crossing point of back emf and the commutation instant. In this aspect too four switch topology minimizes the cost by using the ZCP of three voltage functions, that coincide to six commutation instants rather than using complicated hardware's to carry out phase shift. Theoretical analysis and simulations on MATLAB/SIMULINK were conducted to demonstrate the feasibility of the proposed sensor less method. The cost reduction of controllers for PMBLDCM drives can be considered with the topologies with more than one switch per phase, but less than conventional two

switches per phase. But according to the working of BLDCM, at a time only two phases are conducting. BLDC motor drives with trapezoidal back electromotive force (EMF) using the four-switch three-phase (FSTP) inverter was developed: The four-space-vector scheme and the six commutation modes are based on current control. They used position sensors to achieve commutation control of BLDC motors.

BLDC motor needs quasi-square current waveforms, which are synchronized with the back-EMF to generate constant output torque and have 120 degree conduction and 60 degree non-conducting regions. The synchronization is shown in fig 4.

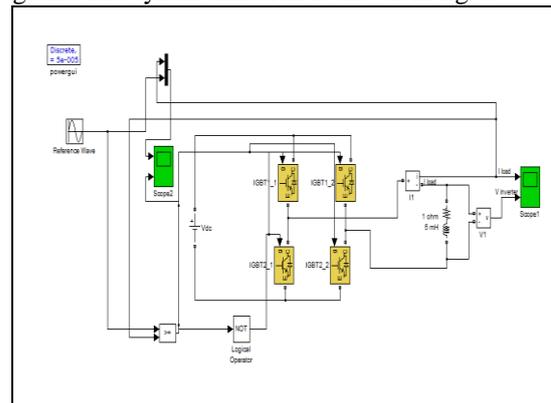


Figure 3. Four Switch converter using hysteresis current control

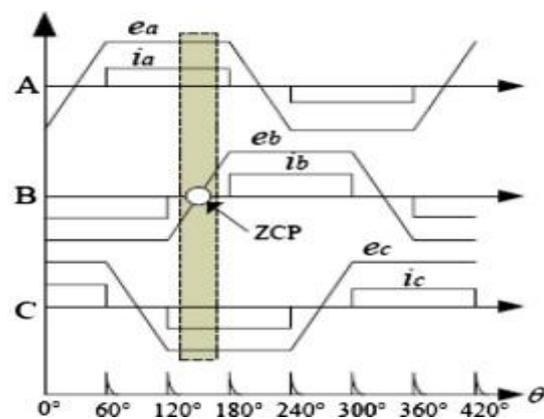


Figure 4. Synchronization of back emf with phase currents.

However, in the four-switch converter, the generation of 120 degree conducting current profiles is inherently difficult. Though cost saving is achieved, it introduces distortions in the uncontrolled phase. This problem is solved by using hysteresis current control. In this method pwm pulses produced by the switching ON and OFF the switch when the phase current crosses the Hysteresis Band. The simulation model is as shown in Figure 3, figure 5 and output waveform is shown in the Figure 6.

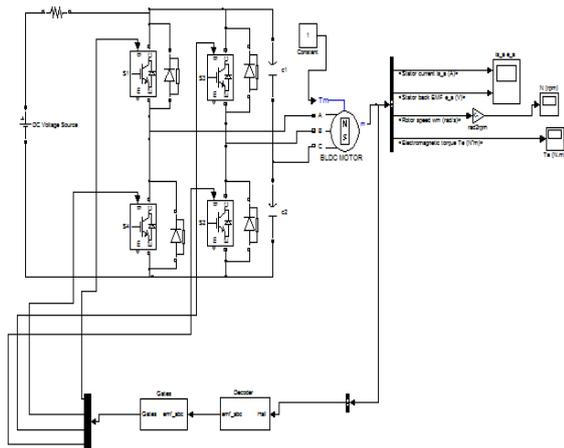


Figure 5. Simulink diagram for four switch inverter fed PBLDC

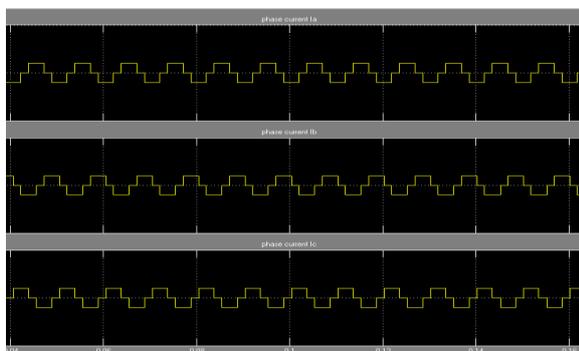


Figure 6. Phase current waveforms four switch inverter fed BLDC motor

IV. Proposed BLDC Motor with Fuzzy Logic Controller

The simulation of BLDC Motor with sensor is controlled by using Fuzzy logic controller. One of the reasons for the popularity of Fuzzy Logic Controllers is its logical resemblance to a human operator. Three hall effect sensors are connected the other end of the motor and they are separated by 120 degree mechanically.

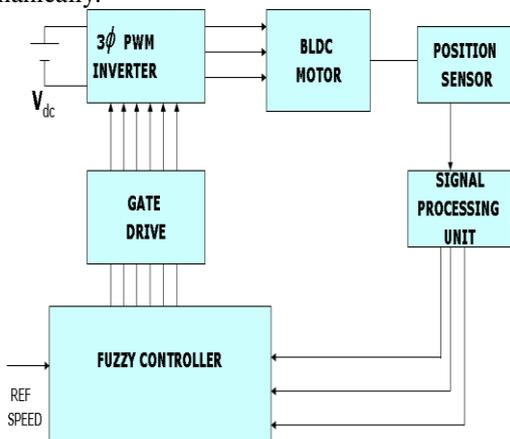


Figure 7. Proposed BLDC motor with Fuzzy logic controller

BLDC motor has three phase windings on stator and Permanent Magnet on rotor. In order to define the shaft Position, rotor position sensor is necessary. The sensor senses the rotor shaft position and signals. The processed signals are given to the fuzzy controller. The output of the controller is used to provide switching signals for the inverter from which the speed of the motor can be controlled. It is shown in figure 7.

V. Fuzzy logic controller

The fuzzy logic Controllers are basically put to use when the system is highly non-linear thereby making the making the mathematical modeling of the system very arduous. The analytical form of the system is not provided, a linguistic form is provided. The precise identification of the system parameters are required. A Fuzzy Logic Controller (FLC) uses fuzzy logic as a design methodology. There are basically three essential segments in Fuzzy Logic Controller. They are Fuzzification block or Fuzzifier System. Defuzzification block or Defuzzifier. This is shown in figure 8.

The first step towards designing a Fuzzy Logic Controller is choosing appropriate inputs which will be fed to the same. These input variables should be such that, they represent the dynamical system completely. The two inputs given are error and change in error. The output is the reference current for the Hysteresis controller. All three membership functions are Triangular. The input and output membership functions are shown in Figures 9 to 11. For the fuzzy controller necessary data required for the simulation is given in Table 1.

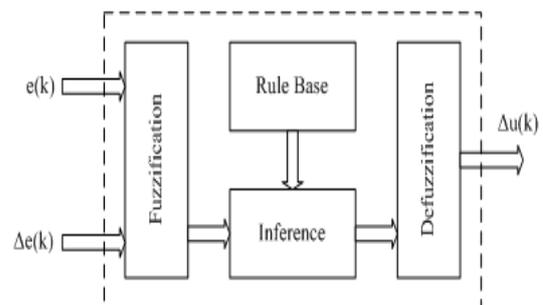


Figure 8. Structure of fuzzy logic controller

name	'FuzzyBlcdc.fis'
type	'mamdani'
and Method	'min'
or Method	'max'
defuzzMethod	'centroid'
imp Method	'min'
aggMethod	'max'
input	[1x2 struct]
output	[1x1 struct]
rule	[1x49 struct]

TABLE 1: parameters for simulation of fuzzy controller

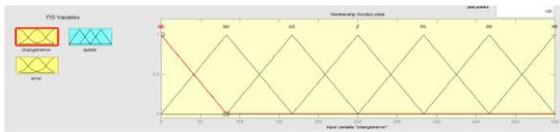


Figure 9. Membership function of error

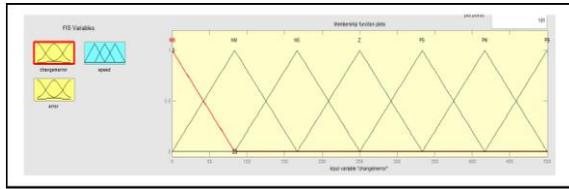


Figure 10. Membership function of change error

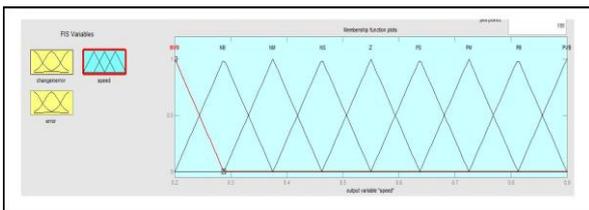


Figure 11. Membership function of reference current

A Defuzzifier is generally required only when the Mamdani Fuzzy Model is used for designing a controller. Mamdani model is preferred here because it follows the Compositional Rule of Inference strictly in its fuzzy reasoning mechanism. Unlike the Mamdani model, the outputs are defined with the help of a specific function for the other two models (first order polynomial in the input variables) and hence the output is crisp instead of fuzzy. This is counterintuitive since a fuzzy model should be able to propagate the fuzziness from inputs to outputs in an appropriate manner.

The inference system of a Fuzzy Logic Controller consists of a number of If-Then rules. If side of the rule is called the antecedent and then side is called the consequence. These rules are very simple to understand and write and hence the programming for the fuzzy logic controller becomes very simple. The fuzzification rule is entered using the rule editor of the fuzzy toolbox as shown in Figure 12.



Figure 12. Rule editor

Simulink model has the BLDC model, Block diagram of the FLC for the speed control of the PMLBDC, the gate pulses from the PWM Gate block. This block in turn receives two inputs - switching signal generated from encoder and duty cycle generated from the fuzzy controller block. The step

change in speed reference and load is given at the pre-specified time. The controller performance is tracked by observing the speed after the input command.

The measured motor speed from the BLDC drive is compared with the reference speed producing the error which is given to the controller in the model. By decoding output of the hall sensor signals, gate pulses for the three phase inverter are generated. The current output from the fuzzy output is fed to hysteresis controller (current limit control) is used for making the phase currents smoother. Simulation results are shown in Figure15-17.

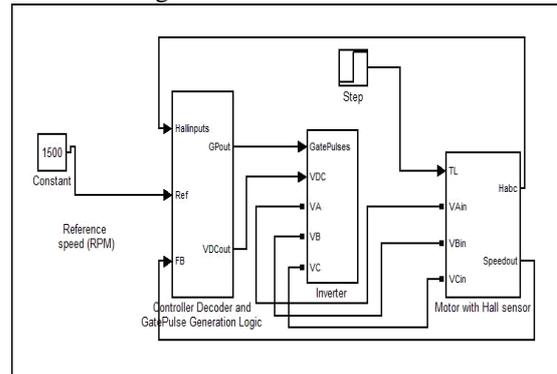


Figure 13. Controller, four-switch inverter and motor model

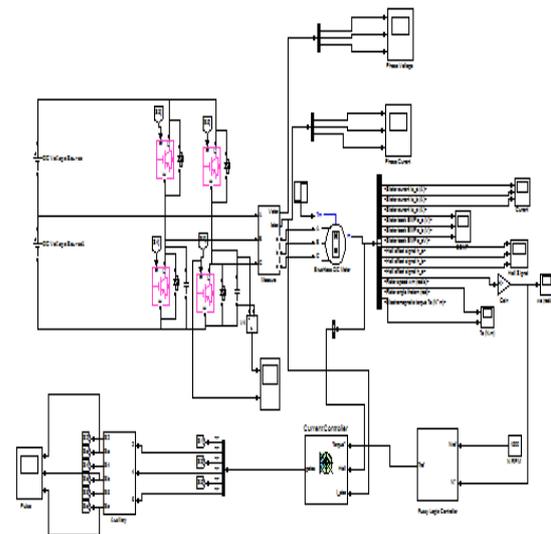


Figure 14 Simulation diagram of BLDC Motor with FLC

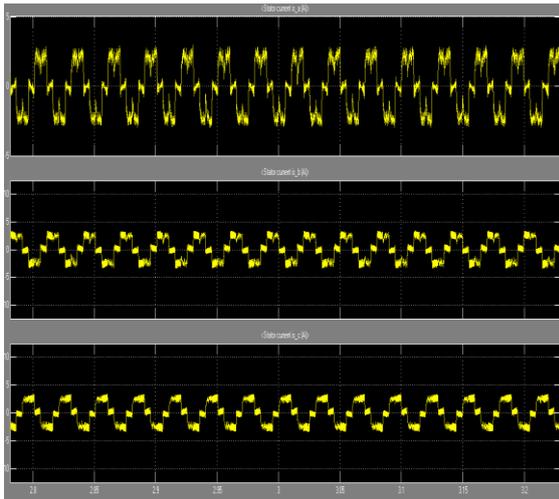


Figure 15. Phase current using fuzzy controller

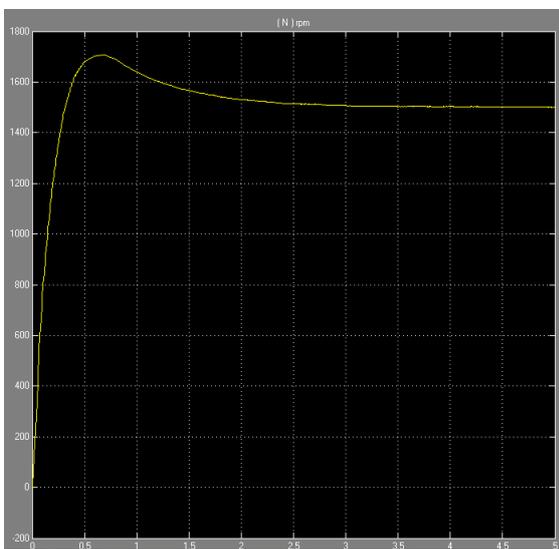


Figure 16. Speed profile of the drive for fuzzy controller

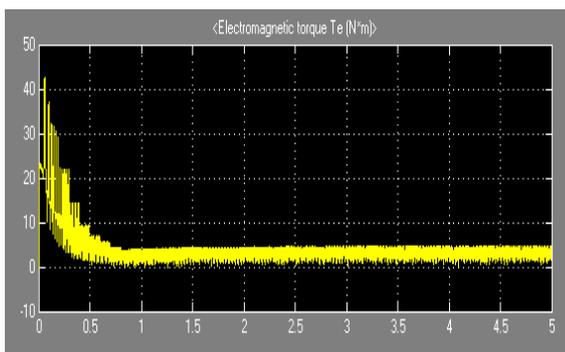


Figure 17 Torque profile of the drive for fuzzy controller

VI. Modelling of four switch inverter fed PMSBLDC with sensor less control

A BLDC motor can be controlled by sensor less control method. The implementation of a low cost, reduced parts BLDC motor is desired with high system reliability. But for reducing the manufacturing cost a feasible sensor less method is developed by

eliminating the position sensors. Also in harsh environments where these sensors cannot function reliably sensor less control is the only choice. Most of the sensors less methods for a six-switch inverter BLDC motor drive are not directly applicable to the four-switch inverter. The main reason is that in the four-switch topology, some methods detect less than six points, and other commutation instants must be interpolated via software. In this aspect too four switch topology minimizes the cost by using the ZCP of three voltage functions, that coincide to six commutation instants rather than using complicated hardware's to carry out phase shift. Theoretical analysis and simulations on MATLAB/SIMULINK were conducted to demonstrate the feasibility of the proposed sensor less method. This paper presents a novel sensor less method for four-switch BLDC motor drive based on zero crossing points of stator line voltages.

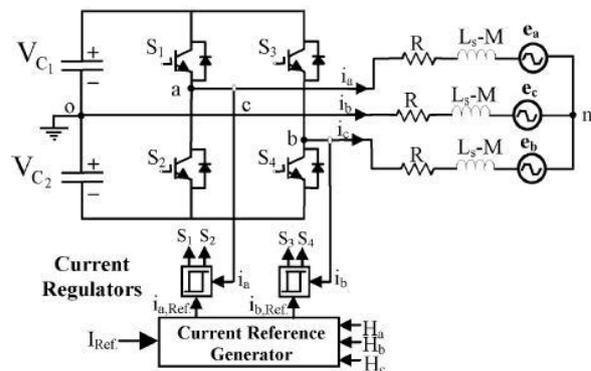


Figure 18. Equivalent circuit of four switch inverter fed BLDC motor drive.

The equivalent circuit of the four switch inverter Brushless DC motor drive is shown in figure 18.

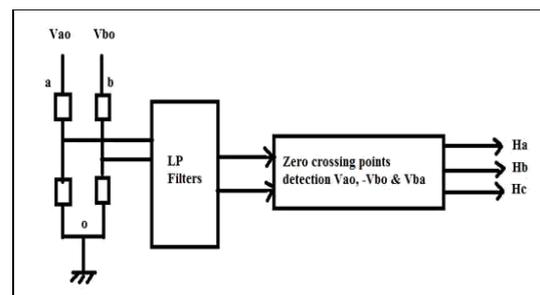


Figure 19. Position Sensing Using Line Voltages

VII. Position sensing using line voltages

In four switch converter topology the third phase is connected in between midpoint of two capacitors. However, in the four-switch converter, current is flowing even at the zero-vectors as one phase of the motor is always connected to the midpoint of the dc-link capacitors. Moreover, the phase which is connected to the midpoint of dc-link capacitors is uncontrolled. Therefore, by detecting the zero crossing points of three line voltages, six commutation points are obtained. From this commutation points the virtual Hall Effect signals are produced.

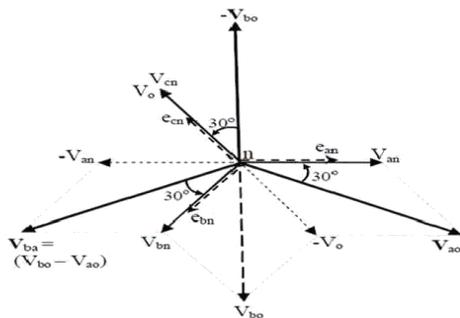


Figure 20. Line to line voltage representation

Three line voltages are derived from terminal voltages V_{ao} and V_{bo} . They have higher magnitude compared to back EMF voltages that is 3 times phase voltages plus drop voltage on the stator impedance. The phasor representation of Four switching topology is shown in Figure 20.

From figure 19 the terminal voltage equation can be written as equation (9) to (11).

$$V_a = i_a(t)R_a + L_a \frac{di_a}{dt} + e_a(t) \quad (10)$$

$$V_b = i_b R_b + L_b \frac{di_b}{dt} + e_{bn} + V_{no} \quad (11)$$

$$0 = R_c I_c + L_c \frac{di_c}{dt} + e_{cn} + V_{no} \quad (12)$$

In a four-switch inverter topology terminal voltages V_{ao} and V_{bo} are oriented 60° together. That means V_{ao} and $-V_{bo}$ lag 30° with respect to e_{an} and e_{cn} respectively. Moreover, voltage $V_{bo}-V_{ao}=V_{ba}$ also lag 30° with respect to e_{bn} . This means that the zero crossing points of V_{ao} , V_{ba} and $-V_{bo}$ can be used to commute the currents in phase A, B and C respectively.

Table II indicate the detailed Switching sequences of four switch converter. Due to the characteristics of BLDC motor, only two phases need to be controlled by the four switches using the hysteresis current control method during each operating mode. Hence this scheme is called the Direct Current Controlled PWM scheme. Because the drive employs the Direct Current Control (DPC) method, in order to make the current as quasi square waveform in accordance with the trapezoidal back emf, motor adopts 120 degree conducting mode and only two phases are energized at one time. So, the current in the two phases has the same amplitude and opposite direction, while in the third phase, the current is zero. Current is regulated to obtain the required quasi-square waveform. Based on the switching sequences shown in table II, the current regulation is brought out by hysteresis current control scheme.

Modes	Active Phases	Silent Phases	Switching Device
Mode I	Phase B and C	Phase A	S4
Mode II	Phase A and B	Phase C	S1 and S4
Mode III	Phase A and C	Phase B	S1
Mode IV	Phase B and C	Phase A	S3
Mode V	Phase A and B	Phase C	S2 and S3
Mode VI	Phase A and C	Phase B	S2

Table II. Switching sequences of four switch converter

A complete simulation of the system is done in Simulink of the MATLAB environment. The system consists of a BLDC motor with the dc link voltage and inverter. The performance of the machine is studied in open loop. A constant speed operation of the drive is simulated in closed-loop. Control is achieved via terminal voltage sensing. The three voltage functions are used to get the commutation points. A voltage divider circuit is used first, followed by low pass filter (second order Butterworth) and then a zero crossing detection circuit to get the virtual hall signals. Zero crossings of VFs are detected using simple comparator circuits, and the virtual Hall sensor signals VHa, VHb and VHc are generated that can be used for current commutation. The virtual Hall sensor signals and the corresponding operation modes are summarized in table III.

Table III
 Commutation logic from voltage functions

Voltage Function	VF _i sign before ZCP	VF _i sign after ZCP	Next mode	H _i H _b H _c
VF _b	Positive	Negative	I	100
VF _a	Negative	Positive	II	101
VF _c	Positive	Negative	III	001
VF _b	Negative	Positive	IV	011
VF _a	Positive	Negative	V	010
VF _c	Negative	Positive	VI	110

VIII. Simulation results

The simulation diagram is shown in figure 21 and results are given in figure 22& figure 23.

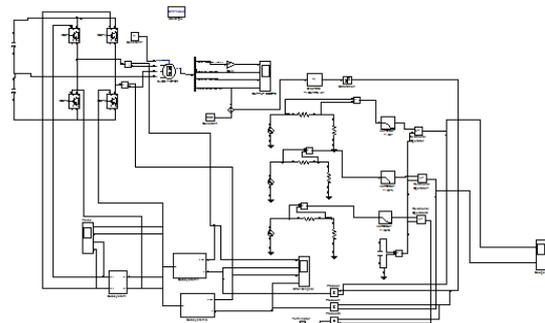


Figure 21. Simulink diagram for four switch inverter fed BLDC motor with sensor less control.

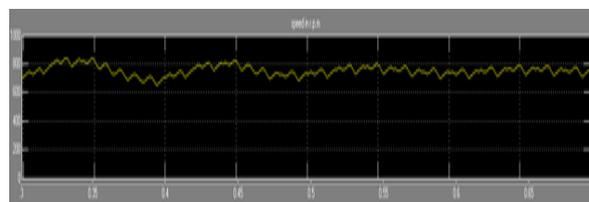


Figure 22. Speed profile of the drive for sensorless control

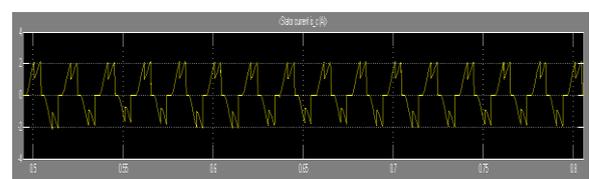


Figure 23. Stator current for phase C

The rated BLDC motor parameters are listed in table III.

Table III Motor Specifications

Rated power	1.03KW
Pole Number	4
Input Voltage	415V
Line-to-Line Resistance	18.7Ω
Line –to –Line inductance	26.82mH
Torque constant	1.0302
Inertia constant	0.0008
Friction factor	0.001

IX. Conclusion

In this paper, first Modelling of Four-Switch Inverter Fed Permanent Magnet Brushless DC Motor is done using Fuzzy controller with the Hall Effect sensors and then with sensor less control by adopting hysteresis current control method. Four-switch converter topology is introduced in this paper where cost saving is achieved by reducing the number of inverter power switches and also by eliminating the position Hall-effect sensors and phase shifters. The measured terminal voltages yields the virtual Hall signals for current commutation thereby giving a sensor less control. The current waveforms are rectangular without any distortion due to the hysteresis control. The sensor less method via terminal voltage sensing will overcome the disadvantages of back emf method. The fuzzy controller i.e sensor control responds faster and smoother to reference speed changes. But if low cost is the primary concern and motor speed is not an issue, then sensor less control will be the better choice. The modelling and simulation of the complete drive system is described in the paper. Effectiveness of the model is established by performance prediction over a wide range of operating conditions. The performance of the PMBLDCM drive with reference to both the steady state and the dynamic conditions is improved with the application of the fuzzy logic controller.

REFERENCES

[1] Pragasam Pillay and R.Krishnan,(1988), "Modeling of Permanent Magnet Motor Drives", IEEE'1988, vol35, No.4. P Pillay and R Krishnan. 'Modelling, Simulation and Analysis of a Permanent Magnet Brushless dc Motor Drive.' *Conference Record of IEEE/IAS Meeting*, 1987, p 8

[2] J. Shao, D. Nolan, and T. Hopkins, "A novel direct back EMF detection for sensorless brushless DC (BLDC) motor drives," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2002, vol. 1, pp. 33–37.

[3] M. Nasir Uddin, Tawfik S. Radwan M. Azizur Rahman, " Fuzzy-Logic-Controller-Based Cost-Effective Four-Switch Three-Phase

Inverter-Fed IPM Synchronous Motor Drive System ", IEEE Trans Ind. Appl Conf Vol. 42, No. 1, JANUARY/FEBRUARY 2006

[4] B. K. Lee, T. H. Kim, and M. Ehsani, "On the feasibility of four-switch three-phase BLDC motor drives for low cost commercial applications: Topology and control," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp.164–172, Jan. 2003.

[5] J. P. Jahns, M. Ehsani, and Y. Guzelaunler, "Review of sensorless methods for brushless DC," in *Proc. IEEE IAS Annu. Meeting Conf.*, 1999, pp. 143–150.

V. P. P. Acarnley and J. F. Watson, "Review of position-sensorless operation of brushless permanent-magnet machines," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 352–362, Apr. 2006.

[6] M. A. Awadallah, M. M. Morcos, "Switch Fault Diagnosis of PM Brushless DC Motor Drive Using Adaptive Fuzzy Techniques " *IEEE Trans Energy Conv*, Vol. 19, No. 1, MARCH 2004

[7] Oh, D.S.; Youn, M.J.; "Automated adaptive hysteresis current control technique for a voltage-fed PWM inverter," *Electronics Letters* , vol.26, no.24, pp. 2044-2046, 22 Nov. 1990

[8] A. Halvaei Niasar, H. Moghbelli, A. Vahedi; "High Performance Torque Control of Brushless DC Motor Drive based on TMS320LF2407 DSP Controller", *International Review on Electrical Engineering Journal*, June 2007.

[10] "TMS320C24x DSP Controllers, Volume 2: Peripheral Library and Specific Devices", Literature Number: SPRU160C, September 1997.

[11] A.H Niasar, Abolfazl Vahedi, and Hassan Moghbelli, "A novel position sensorless control of a four switch Brushless DC motor drive without phase shifter," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp.3079–3087, Nov. 2008.

[12] Tsung Lin, C. Wen Hung, C. Wen Liu; "Sensorless Control for Four-Switch Three-Phase Brushless DC Motor Drives", in *Proceeding of the Forty-First IEEE Industry Applications Conference Meeting (IAS'06)*, Taiwan, Oct. 2006, vol. 4, pp. 2049-2053

[13] J.P. Johnson, M. Ehsani, Y. Guzelgunler; "Review of Sensorless Methods for Brushless DC Motor", *IEEE Industry Applications Conference*, 1999, Vol. 1, pp. 143–150.

[14] R. Krishnan, "A novel single-switch-per-phase converter topology for four-quadrant pm brushless dc motor drive", *IEEE Trans. Ind. Appl.*, Vol. 33, No. 5, pp. 1154-1161, Sep./Oct., 1997.